EXHIBIT "J"

The Energy to Lead

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REVISED DRAFT FINAL REPORT

GTI PROJECT NUMBER 21323

Validation of Installation Methods for CSST Gas Piping to Mitigate Indirect Lightning Related Damage - Revision A

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Executive Summary

Revision to the Final Report

This revision of the report is being issued in order to address a number of typographical errors that were discovered in the original version. Specifically, the resistance per meter of various CSST products as measured by Lightning Technology Incorporated were an order of magnitude too low as shown in the original report. This revision effects Table 3 in the main body of the report and *Table 6 – CSST per Unit Length Resistance, Inductance, and Capacitance* in Appendix B provided by LTI. The corrected values are exactly a factor of ten larger than those from the original report, eliminating the typographical error. If one examines *Table 5 – Resistance, Inductance, and Capacitance Measured on 2-meter CSST Samples* from the LTI report it is seen that the raw data is correct and the error was introduced when the raw data was normalized to one meter lengths.

It is important to note that the incorrect values were not used in any critical calculations or simulations. None of the simulation results have been revised, as the values used in these were provided by the simulation contractor, PowerCET. The PowerCET values are substantially in agreement with the resistance per meter for various CSST products found in the open literature. This revision does not modify any of the conclusions from the original report; it only seeks to correct a typographical error.

Project Objectives

The simulation and analysis described in this report is considered an addendum to the Phase II research program addressing the effectiveness of direct bonding Corrugated Stainless Steel Tubing (CSST) to mitigate damage from indirect lightning strikes. The overall objectives of the research are as follows.

The Phase II project proposed to the NFPA Research Council by SEFTIM sought to validate the effectiveness of direct bonding to earth ground of corrugated stainless steel tubing (CSST) used for the delivery of fuel gas in buildings. The Phase II testing plan addressed the following points:

1. Validate whether or not bonding of CSST is an adequate solution to lightning exposure problem.
2. If bonding is the solution, validate how bonding should be done.
3. If bonding is the solution, validate the size of the bonding jumpers.
4. Determine if bonding should be done at a location or locations other than where the gas pipe enters the building.
5. Determine if alternate methods can be used for safe installation, i.e., separation from other equipment.

There are two areas that the testing plan explicitly does not address.

- The sustained conduction of power line fault current by CSST is outside of the scope of this project. This condition has been shown to cause perforation in prior studies. This issue is properly addressed by circuit protection devices that detect the flow of fault current and disconnect it at the source.
- Direct lightning strikes are outside of the scope of this project. Indirect strikes that induce currents in various residential structures are far more numerous than direct strikes, providing motivation to deal with this category of event.

The added research addresses point 4 by providing simulation scenarios wherein the attachment point of the bonding conductor is simulated at two other locations within the piping system. These simulations speak to the pragmatic considerations of achieving the shortest practical bonding conductor length to provide acceptable levels of damage mitigation. The only attachment point considered in the Phase II work was at the gas service entry. The following sections briefly review the results.

Original Test Plan

The proposed test plan consisted of three primary stages. First, physical testing of CSST established basic material parameters to use in a SPICE model. The resistance, capacitance, and self-inductance of CSST from multiple CSST manufacturers were measured. The dielectric breakdown of the CSST jacket material was measured. The magnitudes of the arc charges and currents required to perforate the CSST were established.

Next, simulations of various scenarios of CSST and direct bond conductor lengths were performed using the measured parameters and SPICE model. The scenarios were chosen to be typical of piping and electrical systems in residential construction. These simulation results were used to provide guidance as to the length and size of bonding conductor that will mitigate and/or eliminate any damage induced by an indirect lightning strike.

Finally, laboratory tests of selected scenarios were performed to verify that the simulation model produced reasonable results. Scenarios that involve extreme lengths of CSST or direct bonding conductor could not be physically tested due to the limitations of real world laboratory equipment. Good correlation between the SPICE model results and the laboratory tests was observed. This allows the SPICE model results to be used as predictors of performance with high confidence.

Results

The laboratory testing established the physical parameters of the CSST samples and that the product from four different manufacturers exhibited substantially uniform parameters. It was also determined that a 10x350 μS waveform of 5 kA or greater was required to create a perforation in the CSST. Based on these data, SPICE model simulations were carried out over a range of lengths for the bonding conductor and a fixed length (100-ft) of CSST. In these simulations, a 6 AWG conductor was bonded to the CSST at the gas service entrance point. These simulations were carried out with the 10x350 μS waveform at 10 kA being introduced at either the gas or the electrical service entrance. The simulations show that the presence of a bonding conductor of up to 50 meters (164 feet) diverted sufficient electrical energy to prevent arc discharge perforation of the CSST. It was further shown that shorter lengths of bonding conductor could divert sufficient energy to prevent any arc discharge whatsoever. Conversely, the absence of any bonding conductor resulted in arc discharge perforation of the CSST in many cases. To verify simulation with practice, selected model scenarios were replicated in the laboratory within the limits of the equipment available. These tests did establish confidence bounds on the SPICE model to within 10 percent. Some additional parametric tests were carried out to verify that the corrugation of the CSST did not create any anomalous inductance compared to straight walled tubing. At no time during the testing or verification was any corrugation to corrugation arcing observed.

Additional Simulations

The NFPA 54 Technical Committee reaction to these results was to limit the bonding conductor length to 75 feet. It was also determined, as supported by the research, that only one point of attachment for the bonding conductor was necessary. However, the request to allow the bonding clamp location on the piping system to "float" was denied, and the current language was left in place. Based on the final proposal accepted by the Technical Committee, additional simulations were carried out under the following test conditions:

- The bond length would be 75 feet or less and the CSST length fixed at 100 feet.
- The location for the bonding connection was varied from the gas service entrance, to the midpoint of the CSST run, and to the gas appliance connection.
- The energy input was 10x350 μS at 10 kA.
- Input at the electrical service entrance and at the gas service entrance were both simulated.

The result of these simulations was that no arcing occurred between the CSST and other conductors within the structure. Given that there was no arcing, the possibility of an arc discharge perforation was

zero. This was true for both 75 and 40 foot bonding conductor lengths and for all three bonding attachment points that were simulated.

Conclusions

The connection of a 6AWG copper direct bonding conductor between the CSST and earth ground diverts sufficient energy to prevent perforation over a wide range of conditions. Simulations of direct bonds of up to 164 feet (50 m) did not indicate any arc discharge perforations with inputs of 10x350 μS at 10 kA.

In the absence of any bonding conductor, a sufficiently energetic event can cause arc discharge perforation.

The data clearly indicates that "shorter is better" insofar as the potential for arcing between the CSST and other metallic conductors in close proximity decreases as the conductor length is shortened. With a sufficiently short bonding conductor, arcing is suppressed entirely, and the possibility of an arc discharge perforation is eliminated.

The additional simulations indicates the protection afforded by a direct bonding conductor of 75-ft can be obtained with several different points of attachment. The results also indicate that a conductor length less than 75-ft will further reduce the level of imposed energy on the CSST.

To optimize bonding effectiveness, it is necessary to choose the point of clamp attachment so as to achieve the shortest practical length of 6 AWG bonding conductor to the electrical ground. The current proposal, which restricts the clamp location to the service entrance, can result in bonding conductor lengths greater than 75-ft in many larger single family houses. Without the ability to move the clamp closer to the grounding electrode system, the current proposed language offers no way to meet the requirement on maximum bonding conductor length.

Introduction

The motivation for this work was to provide the National Fire Protection Agency (NFPA) with sufficient data to make an informed decision as to the efficacy of direct bonding for Corrugated Stainless Steel Tubing (CSST) as a means of preventing lightning damage.

Background

In 2009, the NFPA Standards Council became aware of concerns with the adequacy of the ground bonding provisions contained in NFPA 54, *National Fuel Gas Code,* for CSST in gas piping systems. In that Decision, the Council noted that the record before it revealed both jurisdictional and, more importantly, potential technical issues that called for further attention within the standards development process going forward. The technical issues involved whether the bonding requirements in NFPA 54 for protecting CSST against lightning related damage had been adequately substantiated. A Council Task Group was formed to gather information and make recommendations to the Council on CSST.

The Council Task Group reported back to the Council in a report dated February 11, 2010. The Council's consideration of this report is set forth in Standards Council Decision #10-2, attached as Appendix A. As more fully described in that Decision #10-2, the task group reported a lack of technical substantiation sufficient to ascertain whether the existing bonding requirements in NFPA 54 provided adequate protection from lightning induced surges. Concerned with the lack of technical substantiation, the Council Task Group concluded that a research program was necessary to "identify safe methods for the installation of CSST to protect against lightning induced failure with consequent gas leakage."

After review, the Council agreed with the Council Task Group that CSST would need to receive further attention in the standards development process going forward. To assist the NFPA 54 Technical Committee with input and expertise concerning the lightning-related safety issues related to CSST, the Council also directed that an NFPA 54 CSST Task Group be formed containing expertise from members of the Technical Committees responsible for NFPA 54, NFPA 70®, *National Electrical Code®,* NFPA 780, *Standard for the Installation of Lightning Protection Systems*, and from other appropriate organizations such as those that certify or develop product standards related to CSST. More importantly, the Council directed that the CSST industry or others advocating the continued use of CSST in gas piping systems should validate the safe use of the product through independent third-party validated research and testing that can be reviewed and evaluated by standards developers in a timely way.

On this point, Decision #10-2 states, in greater detail as follows:

> *Over the next full revision currently scheduled to be in the Annual 2014 revision cycle, the industry or others advocating the continued use of CSST in gas piping systems shall validate the safe use of the product through independent third-party validated research and testing that can be reviewed and evaluated by standards developers in a timely way.*

To assist in meeting the requirements of the Standards Council, Decision #10-2, a project meeting was organized by the Fire Protection Research Foundation (FPRF), in March of 2010. The project meeting included experienced members from key stakeholder areas, NFPA staff, NFPA 70, 54, 780, manufacturers, NAHB, and insurance. The meeting led to the framework of the project, a project scope, and a preliminary work plan. A project technical panel was assembled by FPRF, June 2010.

In July 2010 an engineering firm in the lightning area, SEFTIM, was selected by the technical panel. SEFTIM's first task was to complete a literature review and develop a gap analysis to inform a future research project designed to validate installation methods for CSST gas piping to mitigate damage due to lightning events. This initial engineering review and gap analysis work is referred to as 'Phase I' of the project.

The SEFTIM report *Validation of Installation Methods for CSST Gas Piping to Mitigate Lightning Related Damage* (Phase I) was completed and distributed to stakeholders in April 2011. The executive summary of the report concludes with reference to the beneficial role of bonding metallic systems, but that there is a lack of sufficient information to validate installation methods of CSST gas piping to mitigate damage due to lightning events. The summary concludes with the need to perform a targeted testing program to gain greater information as a proposed Phase II of the project.

The project technical panel accepted SEFTIM's recommendation, and also selected SEFTIM to produce the Phase II Test Plan. SEFTIM produced the test plan, *Validation of Installation Methods for CSST Gas Piping to Mitigate Lightning Related Damage, Phase II, Proposal V2* (November 2011), and this test plan was also accepted by the project technical panel.

In April 2012, the sponsors of the project, selected Gas Technology Institute (GTI), to manage the testing phase of the project as laid out in the SEFTIM Test Plan Phase II V2 (November 2011).

The Standards Council accepted this approach in Decision #12-15, August 2012, and also reminded the sponsors that the testing be carried out per the accepted testing plan, SEFTIM Test Plan Phase II V2 (November 2011).

Referring to this test plan:

> *"The Council believes that this test plan must be carried out in order to meet the intent of Decision #10-2.*

Continuing with further clarifying remarks in #D12-15:

> *"The Phase II Test plan need not be conducted by the Research Foundation. It should however, be conducted or managed by a reputable independent, third party testing laboratory or similar entity which undertakes to conduct the testing as set forth in the Phase II Test Plan. In implementing the Phase II Test Plan, there will undoubtedly be a need to work out certain details of how the tests are to be conducted, and judgments about those details will invariably be called for by the independent entity that is chosen to implement the testing. This is to be expected and is acceptable so long as the independent entity makes those judgments and undertakes to do so in a manner that is consistent with the intent and purpose of the Phase II Test Plan."*

In October 2012, GTI presented a project update and initial findings to the NFPA54 Technical Committee. GTI conducted further testing through December of 2012, and simulations in 2012 and early 2013. A report of the findings was provided to the NFPA 54 Technical Committee in May of 2013 followed by a presentation in June of 2013.

The NFPA 54 Technical Committee chose to limit the bonding conductor length to 75 feet. The request to allow the bonding clamp location on the piping system to "float" was denied, and the current language was left in place. Based on the final proposal accepted by the Technical Committee, additional simulations were carried out that treated alternative locations for the bonding conductor. This updated final report provides the data generated by the additional simulations.

Experimental Approach

The overall goal was to determine the efficacy of direct bonding of Corrugated Stainless Steel Tubing (CSST) as a means of preventing damage from nearby lightning strikes. The following is the specific language from decision 10-2:

Concerned with the lack of technical substantiation, the CSST Task Group concluded that a research program was necessary to "identify safe methods for the installation of CSST to protect against lightning induced failure with consequent gas leakage." The CSST Task Group report identified, among the areas that should be addressed, the following:

- *Validate whether or not bonding of CSST is an adequate solution to lightning exposure problem.*
- *If bonding is the solution, validate how bonding should be done.*
- *If bonding is the solution, validate the size of the bonding jumpers.*
- *Determine if bonding should be done at a location or locations other than where the gas pipe enters the building.*
- *Determine if alternate methods can be used for safe installation, i.e., separation from other equipment.*

The data obtained from this work should provide a basis for defining an engineering solution for the grounding of CSST so as to prevent lightning damage. As described in the Executive Summary, the project work was divided into several distinct tasks that were to be executed sequentially. These tasks consisted of the following:

- Parametric Testing that was intended to verify the basic physical attributes of the CSST in the laboratory
- Simulation of several bonding conductor and lightning strike scenarios using the parametric data from the previous task to set up the computer model used for simulation
- Validation Testing of several specific scenarios in the laboratory to verify that the simulation model does provide accurate results
- Conclusions and Recommendations on the efficacy of ground bonding of CSST based on the results of laboratory testing and computer simulation

The overall test approach shown in Table 1 follows that laid out by SEFTIM in their proposal "Validation of Installation Methods for CSST Gas Piping to Mitigate Lightning Related Damage – Phase 2, v2 (November 2011)", included with this report as Appendix B. The one exception to the test matrix below is that AC fault currents were not included in this scope of work; the focus of the subject project was lightning induced transients. The parametric and follow-up laboratory testing was performed by Lightning Technology Incorporated (LTI) division of National Testing Services. The simulation modeling of various bonding scenarios and lightning waveforms was performed by PowerCET Corporation. Project management and technical oversight was provided by GTI.

Test Number	Quick description of test	How to apply the test	Main knowledge that will be gained from the test
Preliminary	Steep front surge current test Insulation withstand test Impedance meter	Directly on CSST length either straight or bended CSST –plate configuration Directly on CSST	• determine the high frequency behavior of CSST • allow computer simulation to be made • determine the withstand voltage of the jacket
1	Main test	On complete configuration with bonding conductor and arc created by a fuse link	• demonstrate the influence of the CSST impedance for all types of lightning stresses. • check the effect of the arc on CSST depending on current, waveshape, CSST length and bonding conductor length • determine maximum values for bonding conductor length without additional bonding, based on tests combined to simulations
2	Power fault current test	Inject a power fault current to CSST wall through an arc created by a fuse link	• check ability of CSST to withstand small power fault current for a long time and higher power fault current for a smaller time

Table 1 – Test Program from SEFTIM Proposal Phase 2-v2 (Nov. 2011) page 15

Parametric Testing

The initial task was to perform parametric tests that characterized the physical properties of the CSST tubing. This phase of the work was carried out by National Testing Services at the Lightning Technologies Incorporated (LTI) facility in Pittsfield, Mass. LTI has provided a thorough and comprehensive report on how this testing was carried out along with the raw data; this is included as Appendix C. This report will be cited extensively during the following discussion.

There were two aspects to this testing: first to capture physical data that could be used to improve the simulation model accuracy and second to determine if the physical parameters varied amongst CSST manufacturers. Samples of CSST piping with representative fittings were obtained from four manufacturers in ½" and 1" diameters. These samples were subjected to the following tests:

- The resistance, capacitance, and inductance per meter of CSST were measured with respect to a ground plane.
- The dielectric breakdown of the jacketing material was tested by placing CSST in proximity to a ground plane immersed in oil and incrementally increasing the voltage level until breakdown occurred.
- The energy required to burn through the CSST was established by intentionally establishing an arc and incrementally increasing the energy until burn through occurred.

The practical details of the test plan were agreed upon by GTI, the CSST manufacturers, SEFTIM, and NTS. The following steps describe the initial parametric testing to obtain electrical characteristics and parameter data on the various CSST products.

- Tests to be performed on, 1/2" OD, non-conductive, dielectric jacketed CSST samples of 1m to 2m in length, terminated with manufacturer specific end fittings to be adapted to standard black iron pipe threaded fittings for ease of laboratory attachments to transient generator return (for high current tests).
- Impedance measurements consisting of per unit length values for CSST self-inductance, parasitic shunt capacitance and DC resistance (all with respect to a 1m distant ground plane below CSST).
- Determine the dielectric strength of the CSST insulating sheaths using the standard 1.2µsx50µs voltage impulse. Potential levels needed are on the order of 25~35kV, peak. Potential applied with respect to flat, grounded electrode flush with CSST outer jacketing.
- Repeat the high current, charge transfer tests of the various non-conductive jacketed CSST products.
    - The jacket was pre-punctured in a repeatable fashion using the hot tip of a soldering iron
    - A 38 AWG wire was placed between the electrode and the CSST wall to reliably initiate the arc
- Charge transfer testing used the following standardized impulse waveforms and current levels as shown in Table 2.
- Measured parameters for the tests would be applied currents, including the associated charge delivered, and degree of CSST wall perforation/melt-through.

	8µs x 20µs	10µs x 350µs
1kA	0.0175C	0.498C
5kA	0.0873C	2.49C
10kA	0.1746C	4.98C

Table 2 – Charged Delivered by Waveform and Current Level

Simulation of Selected Scenarios

This portion of the work would use the measured parametric, electrical characteristic data of various manufacturers' CSST lines as inputs into a lumped parameter, PSPICE based circuit model.

- Analytical model work was based on several scenarios suggested in the SEFTIM Phase 2 proposal such as shown in Figure 1.
- The modeling was actually created/performed by M. Stringfellow of PowerCET.
- The circuit model is then used to provide predictions of voltage rises and/or current divisions at various locations within a modeled 'CSST installation' system, and to serve as basis as an engineering tool towards determining the recommended direct bonding to ground provisions for CSST residential installations.

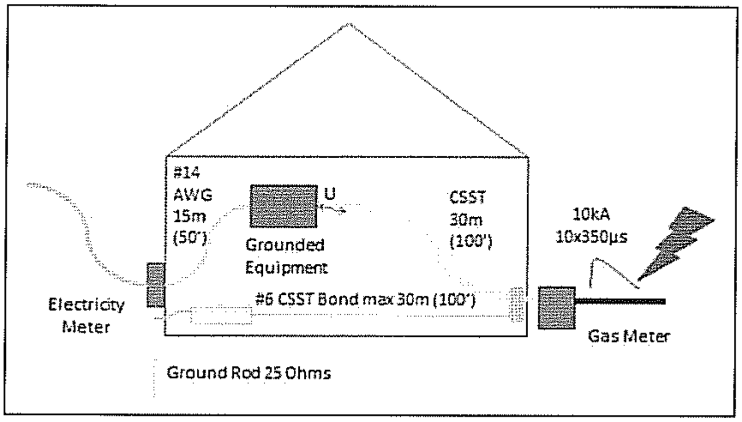

Figure 1 – Simulation Scenario 1

Model Validation Testing

This portion of the work would validate the circuit model via a simplified CSST arc entry test arrangement. A validated model will be a valuable tool in determining the best practices for direct bonding of CSST installations.

- Second series of experimental tests on sections of various CSST lines would be used to validate the results of the analytical circuit model. These tests would consist of recreating a simple CSST to earth ground direct bond arrangement (already modeled), imagined to include representations of the grounding wire, grounding rod, and rod to earth impedances as paths back to the transient generator current return.
- Measured parameters for the tests would be applied currents, voltage rise measurements at grounding elements and degree of CSST wall perforation/melt-through. Only one side of the CSST would likely be grounded for this test, the recommendation being that whatever physical situation was modeled be reproduced in the test lab for purposes of validations of the model results.

Data Analysis and Reporting

The data generated by LTI and PowerCET in the preceding tasks will evaluated by GTI to verify that the model results are reasonable. The validated model can be used to arrive at recommending direct bonding configurations for CSST service entrance grounding best practice. The resulting report will be further evaluated by a panel of industry advisors to verify that the issues have been thoroughly addressed.

Results and Discussions

The following section will provide a high-level synopsis of each aspect of the test program, both experimental and simulation. The detailed supporting data is provided in the reports written by LTI and by PowerCET, which are provided as appendices. What can be drawn from the data will be discussed in detail in the "Conclusions" section. The conclusions at a high level are:

1. The physical properties of the CSST product are reasonably repeatable from sample to sample and across manufacturers.
2. The quantitative level of current and charge transfer that is required to burn through the CSST wall was established during this testing.
3. The simulation model gave results indicating that direct bonding the CSST at the gas service entrance with a 6AWG conductor providing an adequate drain to keep the current levels well below the established burn through level over a wide range of conductor lengths.
4. Further laboratory testing scenarios with side by side simulations showed that the two methods were in good agreement, with a worst case variance of 5%.

Basic Parameter Measurements

The physical properties of samples of CSST tubing from four manufacturers were measured both to inform the simulation model and to verify uniformity across manufacturers. The test articles provided by the manufactures consisted of 2 meter lengths of CSST tubing already made up with the end connectors as shown in Figure 2. These were provided in both 0.5 inch and 1 inch diameters. Also provided were typical direct bonding clamps as would be applied to black iron pipe (BIP) immediately adjacent to the point where the CSST and BIP are joined.

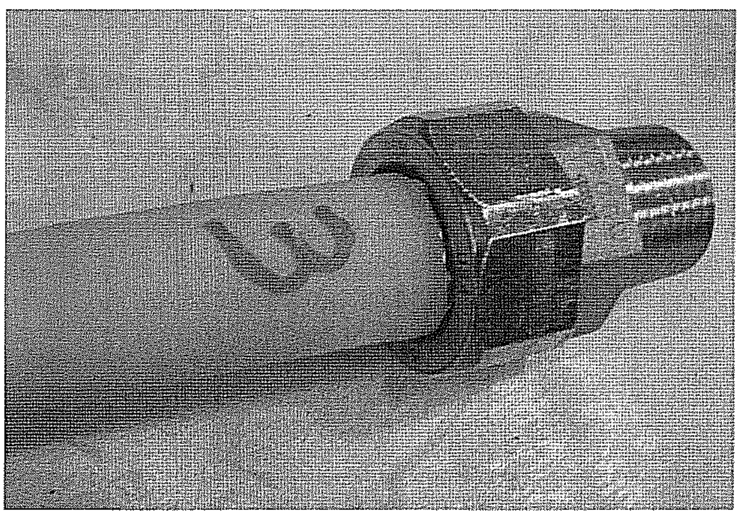

Figure 2 – Typical Test Article from Manufacturers

The first round of physical tests was designed to capture the typical resistance, inductance, and capacitance per meter of CSST product. The typical set up was to suspend one of the provided test articles above a grounded surface as shown Figure 3. A set of precision meters were hooked to the test articles and the values recorded. The detailed procedures for calibrating this set up and the methodology for the measurements can be found on pages 8 through 18 of Appendix C.

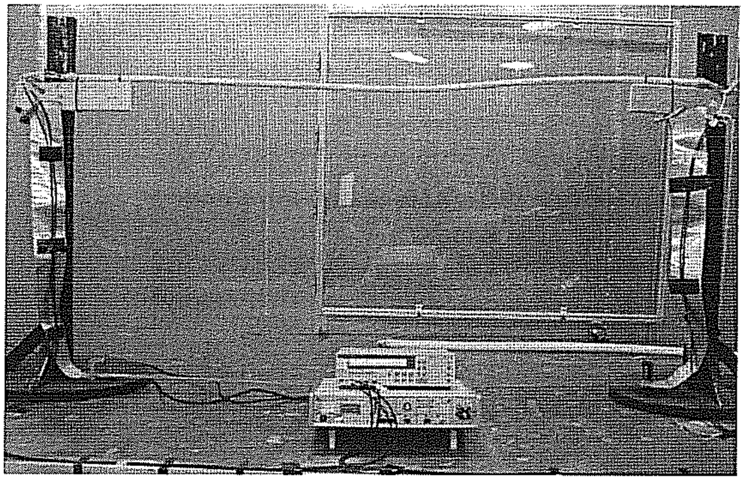

Figure 3 – Typical Impedance Measurement Set Up

The LTI measured values for the various impedance parameters for the CSST test articles were normalized to a per unit length and recorded. The values are given in Table 3. Section 6.2, page 10 of Appendix C provides insight as to the reasons for the 0.5 inch tubing from Manufacturer B exhibiting higher resistance than that from other manufacturers. In short, the test articles were provided with the brass end fittings already applied; these were tested by LTI as received. The fitting to tubing resistance is also included in the measurement and, in this instance, added resistance. Were the tubing measured without the end fittings, the bulk properties of the CSST would be more uniform.

Table 3 – Impedance Properties of CSST (Revised)

Test No.	CSST Manufacturer	CSST Diameter (Inches)	DC Resistance (mΩ/m)	Self Inductance at 10 kHz (μH/m)	Shunt Capacitance at 10 kHz (pF/m)
1	A	0.5	71.32	2.39	0.428
2		1	43.27	2.42	0.487
3	B	0.5	199.13	2.37	0.413
4		1	47.18	2.52	0.446
5	C	0.5	72.89	2.47	0.37
6		1	47.18	2.63	0.378
7	D	0.5	73.54	2.34	0.34
8		1	43.53	2.52	0.404

In addition to the impedance components of resistance, inductance, and capacitance the dielectric breakdown voltage of the CSST jacket material was also measured. This measurement required the use of a specialized high voltage generator capable of raising the CSST test items to a potential in excess of 30kV. The high potential is developed between the test item and a grounded metal plate. In order to prevent spurious arc flash over from occurring, the section of the CSST under test and the metal plate were submerged in an oil bath. The test sample is inserted into the oil bath and connected to the HV generator; the potential applied to the sample is gradually increased until a breakthrough of the coating is achieved. The sample is then repositioned so that an undamaged portion of the coating is adjacent to the ground plate and the procedure repeated. A total of ten breakthroughs were accomplished for each size and manufacturer to provide statistical significance. The set-up is shown schematically in Figure 4 and the detailed procedure with photographs can be found on pages 12 through 24 of Appendix C.

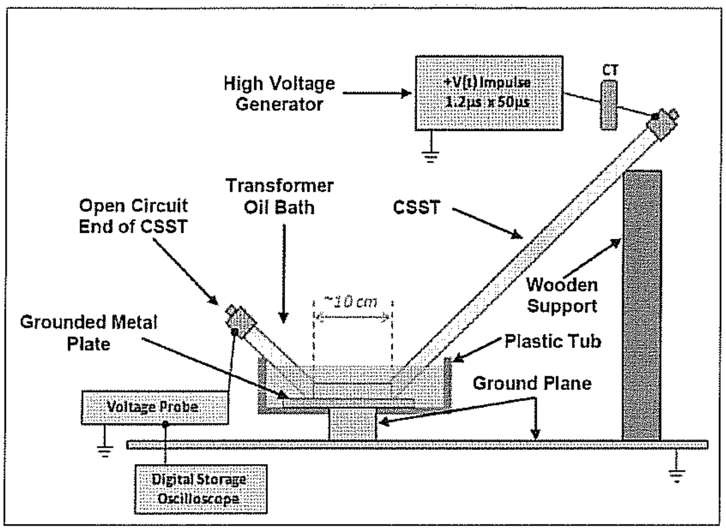

Figure 4 – High Voltage Withstand Test Setup

The general findings of the dielectric breakdown testing are given in Table 4. The data is a composite of 10 tests performed for each manufacturer and CSST diameter. AS can be seen from the data, the dielectric breakdown voltage is fairly uniform with the exception of manufacturer B. This variance is caused by a thicker polyethylene jacket than that found on the other three manufacturers, so the result is not surprising. The thicker jacket material probably contributed to the higher contact resistance between the tubing and its end fittings that was seen in the previous discussion of resistance per unit length. The supporting data for all of the test runs is provided on pages 24 through 57 of Appendix C.

Table 4 – Average Dielectric Breakdown Voltage by Manufacturer

Size/Mfg.	A	B	C	D
0.5 inch	32.9 kV	55.5 kV	30.6 kV	30.8 kV
1.0 inch	35.8 kV	60.6 kV	35.8 kV	37.8 kV

High Current Damage Tolerance Testing

A series of tests were carried out by LTI to quantify the conditions that are required to cause damage to CSST product. For this series of tests, an arc was intentionally created at the wall of the CSST and all of the available current was passed through this arc. This test was performed for multiple samples of CSST from each manufacturer and each diameter for a total of 175 test pulses. The general experimental set up and calibration for this test series is detailed on pages 57 through 64 of Appendix C.

A typical 8x20 µS waveform is shown in Figure 5. The double exponential waveform is the standard for lightning testing and some discussion is in order. The first number expresses the number of microseconds required to reach the peak test current, the second number, the microseconds required for the current to decay to 50% of its peak value. The upper of the two figures shows the current level as a function of time; the lower figure is the total charge delivered by the waveform which is found by integrating the current over time. From this discussion, it can be seen that a peak current must also be specified to completely describe the test waveform. The other standard waveform that is often used for lightning testing is 10x350 µS with a specified peak current. There is discussion in the literature (ICLP2004-74) of the 100x1000 µS waveform but it is not widely adopted as a test standard for two reasons: there is not sufficient observational evidence that many real strikes fit this envelope and it is difficult to produce this waveform in the laboratory at any great current level.

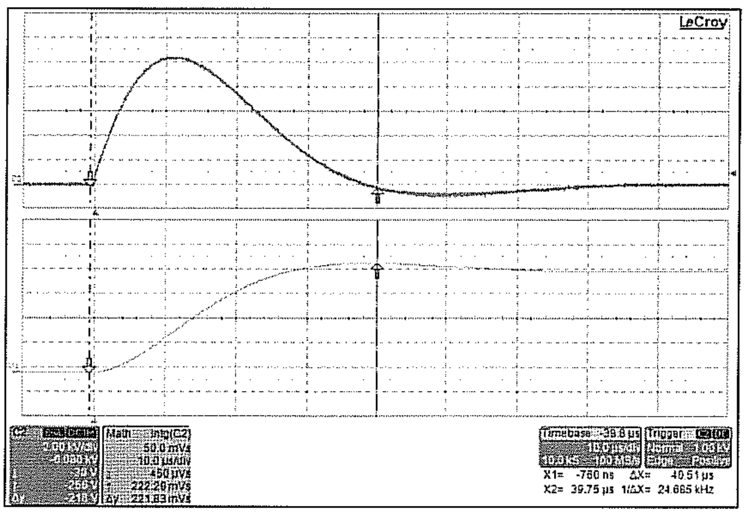

Figure 5 – Typical 8x20 µS Current and Charge Waveforms

Two series of tests were run: one using the 8x20 µS waveform and a second using the 10x350 µS waveform. Each waveform was run at three different current levels: 1 kA, 5 kA, and 10 kA. The complete damage tolerance test results, photographs, and numerical data can be found on pages 64 through 78 of Appendix C. A high level synopsis of the results follows.

The arc was created at a specific point on the test sample in the following manner. First, a small hole was placed in the polyethylene jacket using the tip of a heated soldering iron, exposing the metal. A pointed electrode is placed near to the opening and a short length of 38AWG wire is placed between the CSST and the electrode. This "initiator" wire is vaporized almost instantly by the current pulse but establishes a bridge of ionized air that directs the arc where it is required. The pointed electrode is connected to the output of the current generator and the far end of the CSST is connected to the generator ground, completing the circuit. This arrangement is shown schematically in Figure 6.

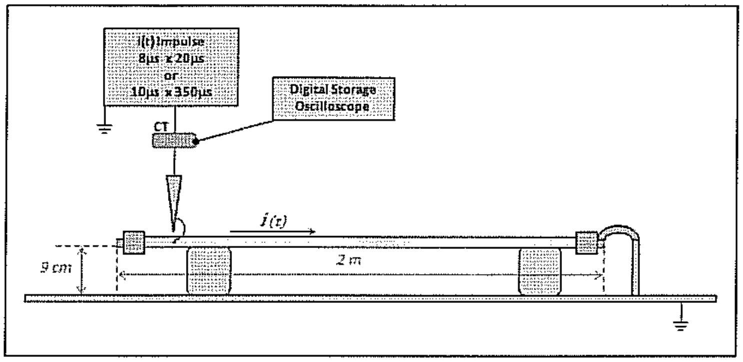

Figure 6 – Arc Damage Tolerance Test Set-Up

The initial series of 8x20 µS waveform tests did not produce any perforations of the CSST samples at the 1 kA, 5 kA, or 10 kA current levels. There was, however, some discoloration and burn marks around the arc entry point. The test series was repeated using the 10x350 µS waveform with a similar result for the 1 kA current level: discoloration and small scale melting without perforation. Figure 7 shows the damage typical of these arc flashes that do not result in perforations. Figure 8 summarizes the data for the entire 8x20 test series as charge delivered versus peak current. The three current levels (1kA, 5kA, 10kA) are clearly visible as is the linear relationship between them.

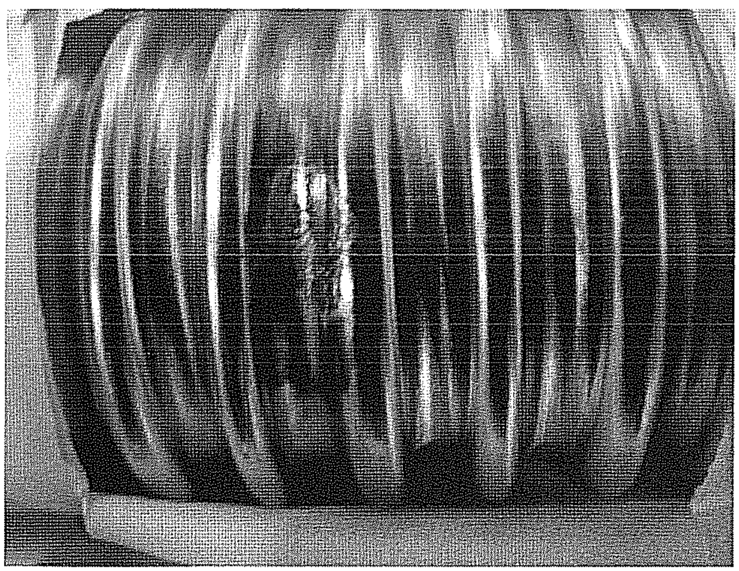

Figure 7 – Typical Damage from 8x20 µS Current Pulse

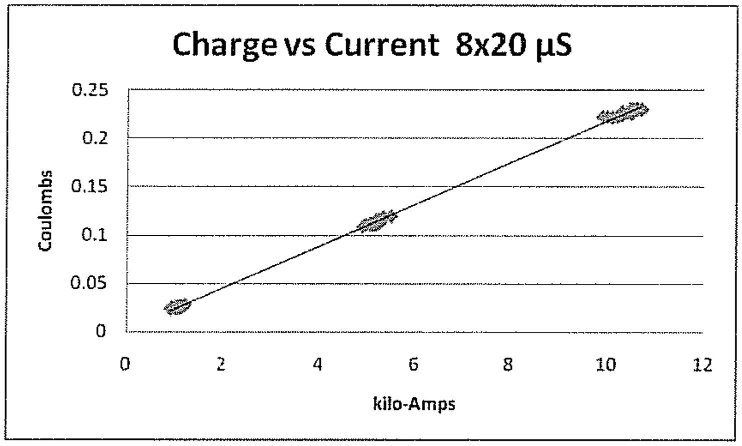

Figure 8 – Damage Tolerance Data for 8x20 µS Current Pulse Series

At the 5 kA and the 10 kA current levels the 10x350 µS waveform did consistently produce perforations in the CSST wall. At this level, each test delivered 2.5 of 5.0 Coulombs of charge respectively. A typical perforation caused by these conditions is shown in Figure 9. The cumulative data for all of the test pulses is shown in Figure 10. In this representation the upper line of data spans all of the 10x350 test pulses: the red points represent perforations (P) and the blue points, no perforation (N). The 8x20 data points are included in green in order to provide scale perspective of the testing regime. This data begins to outline the safe operating zone for CSST subjected to lightning induced transient current.

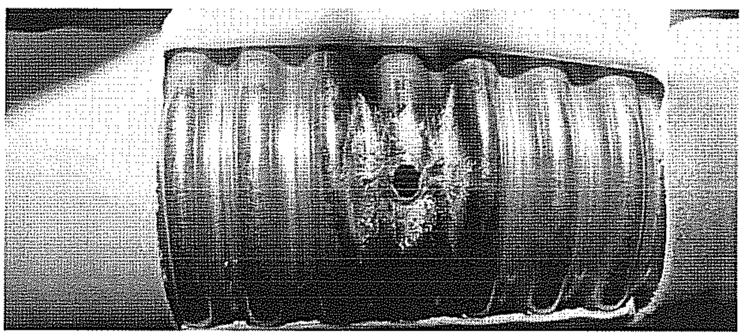

Figure 9 - Typical Damage from 10x350 µS Pulse at 5 kA

Initial Simulation of Direct Bonding

Using the data from the physical measurements performed by LTI, a set of initial simulations was performed by PowerCET. Figure 11 shows the set up for a Simulation Program with Integrated Circuit Emphasis (SPICE) model for the Scenario 1 simulations. These simulations were provided to GTI by PowerCET as a PowerPoint presentation. The entire presentation is available as Appendix D.

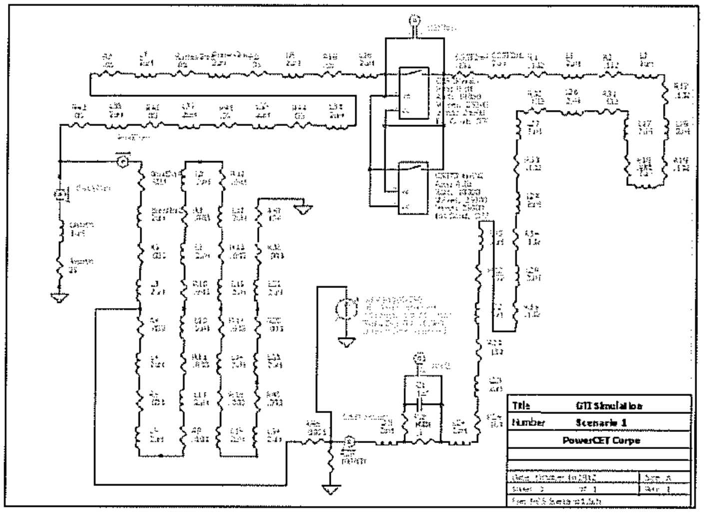

Figure 11 – Typical SPICE Simulation Model

Three different scenarios were simulated in this first round of testing. The basic scenario consists of a direct bond conductor attached to the gas system at the point of transition between BIP and CSST; this scenario assumes that the current pulse enters the residence through the gas line, as shown in Figure 1. Two other scenarios were also modeled: one wherein the CSST is run through a manifold that is also grounded through a 14AWG copper conductor (Figure 12) and a final scenario in which the transient current enters the residence through the appliance electrical connection (Figure 13).

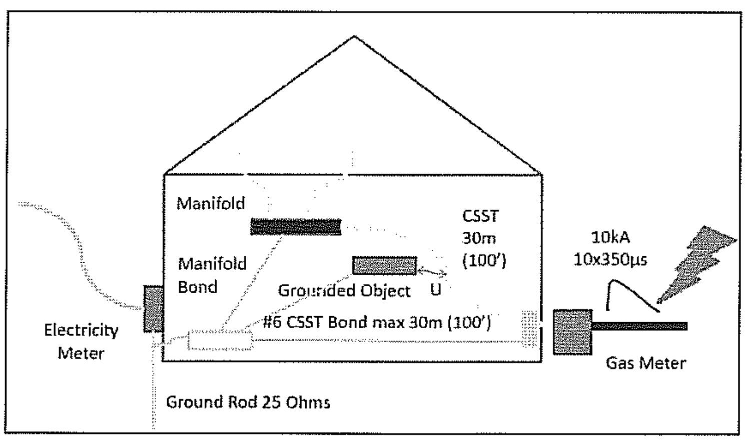

Figure 12 – Scenario 2 with Manifold Bond

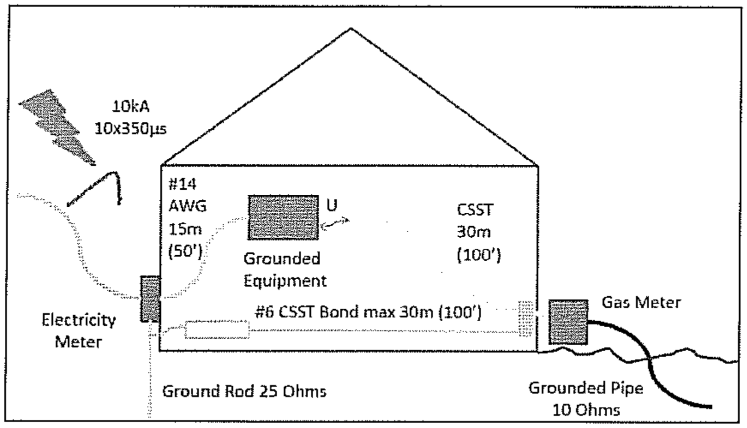

Figure 13 – Scenario 3 Simulation of Current Entering Through Electric Service

The following are the salient points of these simulations:

- All three simulated cases were modeled with the 10x350 µS waveform at 10 kA, representing a severe lightning event, but short of a direct strike.
- In all three simulations one case was run with no direct bond applied at the gas service entrance; in all cases a perforation of the CSST was indicated when the direct bond was absent.
- Additional test cases were run with varying lengths of 6AWG direct bonding conductor applied at the gas service entrance; no perforation of the CSST was indicated in any case where a direct bond was connected.
- For this initial set of simulations the bond length was varied from 13 feet to 98 feet (4m to 30m). Later simulations were run out to 164 feet after validation testing. In no case where a bond was attached was perforation indicated.
- The addition of the manifold bond created a 20% decrease in the arc charge passed but also had the side effect of prolonging the duration of the arc. Later analysis shows that these two effects may cancel one another.
- For perspective, the addition of a 98 feet length of 6AWG direct bond versus no direct bond decreases the arc charge passed by 1700% in the same simulation sequence.
- The addition of the manifold bond made the decrease 2200% versus the unbonded case.

The cumulative data for all simulations of CSST with direct bond conductors is given in Figure 14. The right-most point in the data set represents a simulated bond length of 164 feet (50m) for a Scenario 1 case. The data set also includes the Scenario 2 and 3 cases which introduce some scatter into the data. The simulation data is then overlaid with the damage tolerance testing data in Figure 15 as the purple points. The simulations that did indicate perforations would fall on the same trend-line as the 10x350 P (perforation) series. This gives some perspective on how the addition of the direct bond affects the behavior of the system. Displaying the data in this fashion provides guidance as to which region of this data space constitutes a safe operating area for bonded CSST.

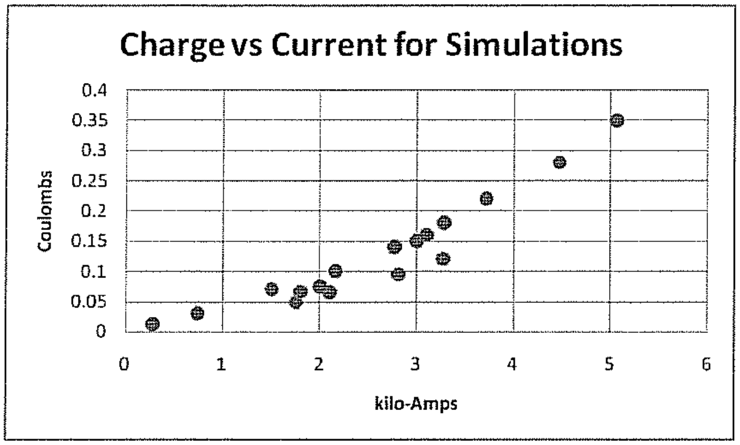

Figure 14 – Arc Charge versus Peak Current for Simulations

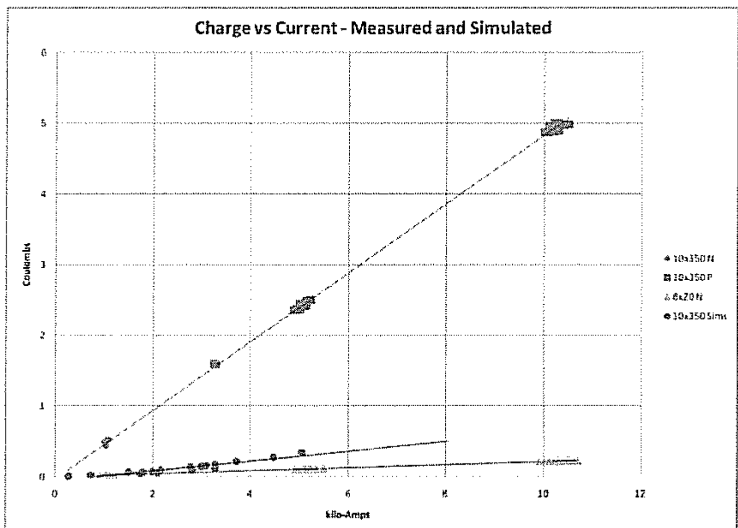

Figure 15 – Measured and Simulated Cases Compared

Additional Simulation Results

An additional set of simulation scenarios was performed in September of 2013. These scenarios replicate the first round in terms of energy injection and CSST length. The variation in this set of scenarios is that the point of ground bond attachment is varied to now include the gas appliance served by the CSST and the mid-point of the CSST run. The motivation for these additional scenarios was the 75 foot limit on the bonding conductor set by the NFPA 54 Research Committee. The ability to move the bonding point addresses the pragmatic concerns of how to install the shortest bonding conductor practical. Figure 16 and Figure 17 show the variation in the bonding conductor attachment point.

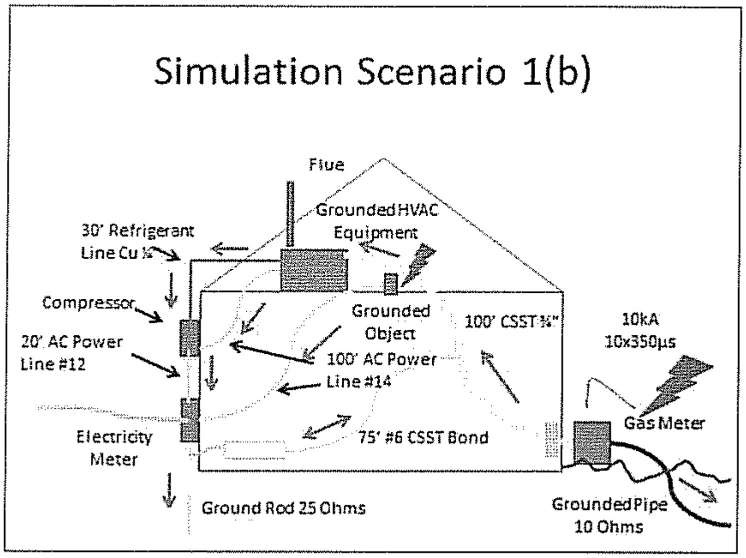

Figure 16 – Variation B of Scenario 1

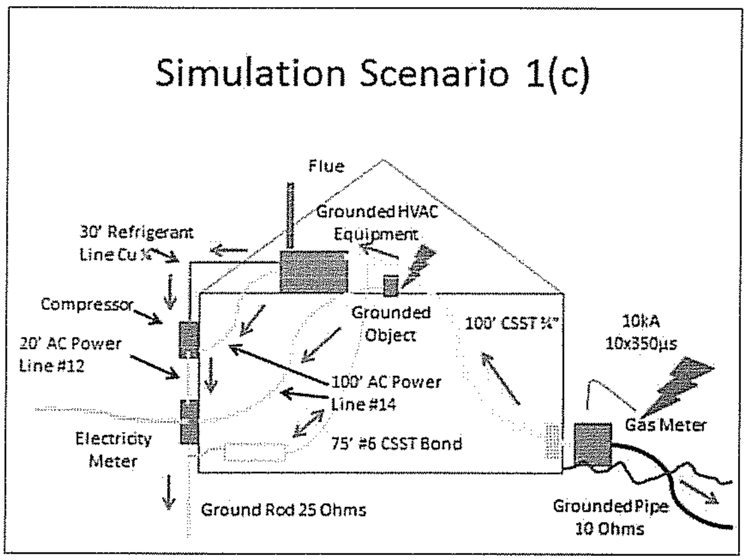

Figure 17 – Variation C of Scenario 1

The general finding of the additional simulations were that varying the attachment point of the bonding conductor did not degrade its effectiveness. Simulations of 75 foot and 40 foot conductors were performed for the various attachment points. The following is a direct quote from the PowerCET final report that is provided as Appendix E.

The recent study, which described a more realistic scenario of gas piping serving a furnace-equipped HVAC system and a more conservative bonding conductor length of 75 feet, showed that voltages between the CSST and grounded objects never approached flashover values for the assumed indirect strike wave of 10kA, 10x350µs.

The additional simulation data indicates that a bonding conductor of 75 feet or less suppresses both arcing and the possibility of perforation. The data also indicates that the protection against indirect lightning strikes provided by the bonding conductor is insensitive to the attachment point of the bonding clamp. The pragmatic issues of installation can be addressed by choosing the shortest path to earth ground that is available.

Laboratory Validation of Simulation Results

A further series of tests were carried out by LTI to verify that the results of the simulation model did indeed provide an accurate prediction of real world conditions. Several simplified Scenario 1 test cases were set up in the LTI laboratory and compared with the corresponding simulation. The detailed description of the set up and execution of these tests with resultant data is given on pages 78 through 97 of Appendix C. In addition to the data reporting provided by LTI, Appendix E from PowerCET provides an analysis of the follow-up testing. These tests were witnessed by personnel from PowerCET and GTI, so the feedback on agreement with simulation model was immediate.

Another issue that was dealt with during the validation testing was measurements of CSST inductance. This was done in order to address concerns that either the corrugation geometry or the magnetic properties of the stainless steel causes CSST to have unusual inductance characteristics. There have been instances where adjacent corrugations show arc damage, leading to the conjecture that the arc can travel "ridge to ridge". A much more likely scenario is that consecutive arcs struck from an external conductor as described in Appendix C, page 65: the raised portion has a sharper curvature and hence greater electric field with respect to external conductors.

As noted earlier in the report, LTI measured the inductance of CSST by the method called out in the SEFTIM proposal: suspending it a known distance above a ground plane. While this method is theoretically sound, it is difficult to implement in the laboratory. The return current at either end of the CSST sample must be shielded in order for it not to interfere with the measurement. The shielding may interfere with the measurement by bringing a portion of the ground plane close to the item under test. An alternative measurement method was suggested by PowerCET that minimized these sources of error.

The CSST inductance was measured during the validation testing by an alternative method of creating two-turn coils of CSST with a know diameter. Coils of 0.5 inch and 1inch diameter CSST were made and suspend on wooden stands 5 feet from the floor to isolate them from the environment. The inductance of these coils was then measured with a sensitive LCR meter. The inductance values found were nearly identical with those of straight walled tubing of the same OD. These inductance values with then used in subsequent simulations with good effect, as will be seen. These observations do not support the premise that CSST has unusual inductance properties due to geometry or material. Pages 28 through 30 of Appendix E provide a technical discussion of this measurement method.

There has also been discussion of the CSST providing a "waveguide" for the transport of high frequency electromagnetic energy. If one examines the specifications for commercially available circular waveguides several interesting facts emerge. Low-loss commercial waveguides have very high tolerances for uniformity and eccentricity. Stated another way, the optimum waveguide will have a constant cross sectional area and be perfectly round. There is also a high tolerance on the flatness of the interior finish for commercial waveguides. Given that CSST undergoes several changes of cross section per inch, it will provide a poor waveguide at best.

Not all the simulated cases of the 10x350 μS waveform at 10 kA can be reproduced in the laboratory. The limitation is governed by the internal impedance and charge storage capacity of the current pulse generator in combination with the impedance of the CSST and grounding system. As the lengths of the CSST and direct bond increases, higher voltages are required to maintain the waveform shape. The current generator in use has an upper operating limit of 36 kV and a current output limited by the load impedance. The series of verification tests were run with CSST sections 15 feet in length and varying

lengths of direct bond conductor. Figure 18 shows the typical set up for this test series. The current pulse is launched from the generator in the background; the CSST and bond wire under test extend into the foreground.

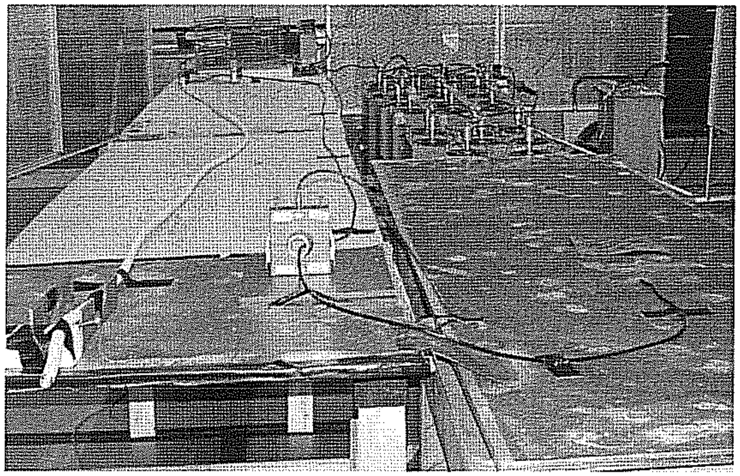

Figure 18 – Model Validation Test Set Up

Figure 19 and Figure 20 are illustrative of the results of the arc charge and current validation testing; they provide the measured and the predicted results of a test scenario respectively. In this particular instance a 32 feet (10m) bond wire was attached to the test section of CSST. In all instances, the amount of measured charge transferred through an arc (if one were present) agreed to within 10% of the simulation predictions. Figure 21 shows some of the validation test data overlaid with the simulations. The figure shows that the all the data fits the linear trend predicted by the model. The laboratory testing was able to test some regions of higher charge and current than the initial simulations without producing any perforations of the CSST. From this finding it is reasonable to assume that extrapolating the model to direct bond lengths beyond 100 feet (30 m) would still give good results.

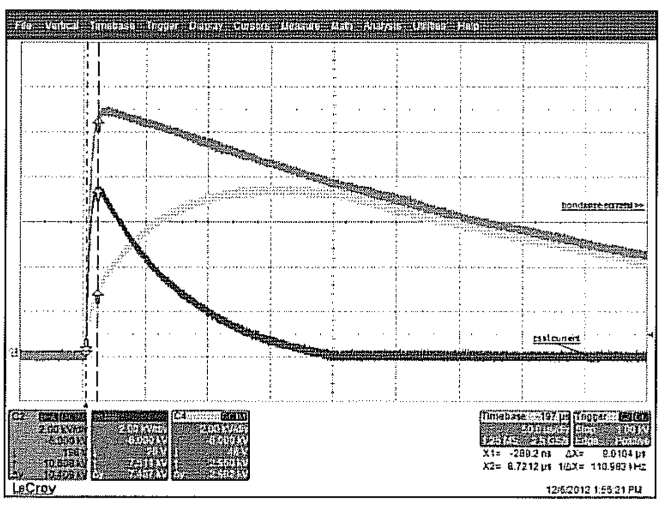

Figure 19 – Validation test 0.5 inch CSST with 32 foot bond wire

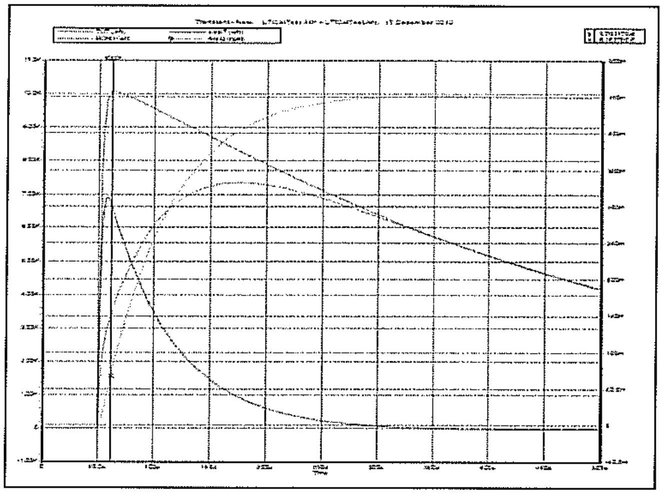

Figure 20 – Simulation of 0.5 inch CSST with 32 foot bond wire

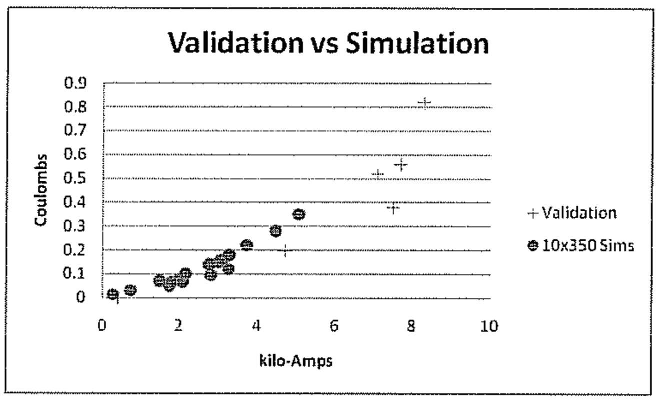

Figure 21 – Model Validation Data versus Simulations

Analysis of Results

In Appendix E, PowerCET asserts the premise that the likelihood of damage to the CSST can be predicted by both the amount of charge available to the arc and by the duration of the arc in time. The addition of a direct bond conductor provides an additional path to drain the charge from the CSST, shortening the duration of any arc or eliminating altogether. When the duration is shortened, the total charge passed through the arc is also reduced. GTI's analysis of the data, both measured and simulated, supports this premise.

Figure 22 shows the composite of the various data sets plus an "Additional" set of damage tolerance tests that were run during the validation tests. All of these additional tests resulted in perforations. A discussion of these tests can be found on page 10 of Appendix E; the raw data at the end of Appendix C.

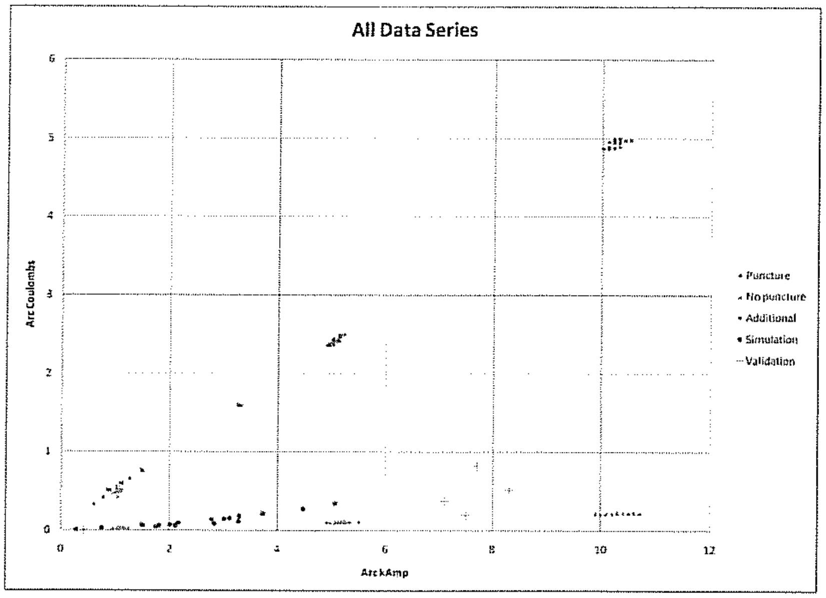

Figure 22 – All Data Sets Charge versus Current

Figure 23 shows this data on an expanded scale. At first glance one sees a very close boundary between the "Additional" perforations that were generated during validation testing and some of the no perforation cases of the initial testing. At least one of the validation test cases that did not produce a perforation is close to the boundary. Also note that the simulated cases of direct bonding are generally far from this boundary.

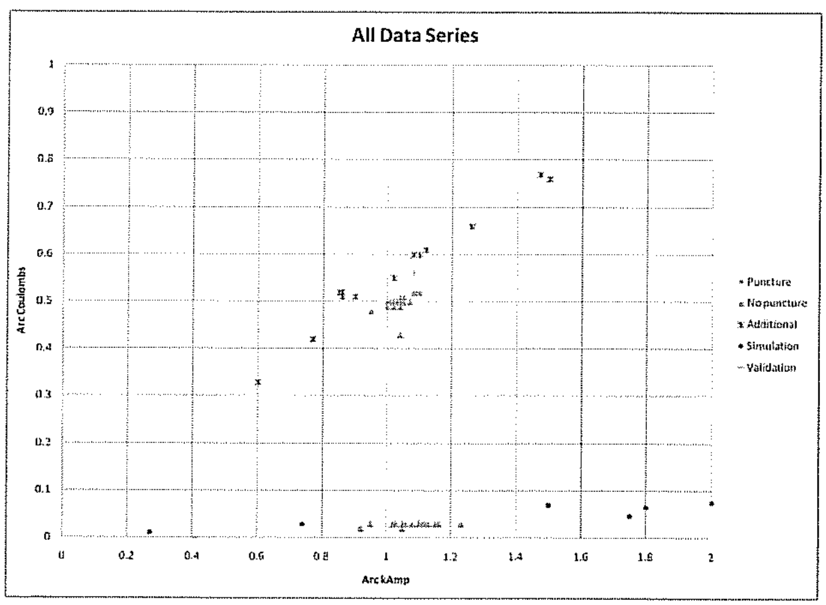

Figure 23 – All Data Sets Expanded Scale

There is an alternative way of viewing the data that is more fruitful: it is possible to extract a rough duration of the arc from the data by the following means. The current through the arc, defined in Coulombs per second, gives a rate at which the charge passes through the arc. From many of the measurements and simulations we also have the total charge dissipated by the arc. We can scale the average current through the arc using 0.5*I-peak; this scaling is implicit in the double exponential waveform as described on page 4 of Appendix B (SEFTIM proposal). The approximate duration of the arc in microseconds is given by the following, where Q is the number of Coulombs passed by the arc and the peak current is given in KiloAmps.

$$t = (1000 * Q)/(0.5 * Ip)$$

If we now plot the data series in terms of arc charge versus the arc duration, there is a much clearer separation of the region in which the bonded CSST can operate from that where there is demonstrable damage. Figure 24 shows all the data plotted in this fashion. All of the simulated bonding conditions and the bond validation test data have arc durations of 200 μS or less whereas all the experimental perforations to date have arc durations in excess of 900 μS.

Figure 25 shows a damage criterion proposed by PowerCET that accounts for both the charge and duration of an arc that substantially agrees with our observed data. It implies that there is a value of Q*t above which damage can be expected. PowerCET cites studies for aircraft skin that indicate that a value of Q*t = 300 would be a reasonable estimate of this boundary condition. Figure 26 shows the test data on a log scale similar to the previous figure; the boundary line Q*t=300 is overlaid on the data sets. Clearly all the experimentally observed perforations are above this line. Further work could refine the position of the boundary but the trend is clearly shown.

A set of Scenario 1 simulations are given in Table 5 with arc charge time products calculated. The simulations provide the peak currents and arc charges out to a bond length of 198 feet (60m). At this length, the Q*t product is roughly 70. As we have seen from the experimental results, the boundary where perforation begins is in the vicinity of Q*t=300. This would indicate that there is reasonable latitude that one can exercise when choosing the bond conductor length.

It is also a corollary that perforation can be expected where the values of t or of Q become extreme; this is not a surprising result. It has been shown in previous studies that sustained (long t) fault currents from AC power lines will cause damage. Direct lightning strikes can provide 50 kA (large Q) or more in pulses of short duration. Both of these scenarios are outside of the scope of this work. Future work could refine our quantitative knowledge of the Q*t conditions required to cause perforation.

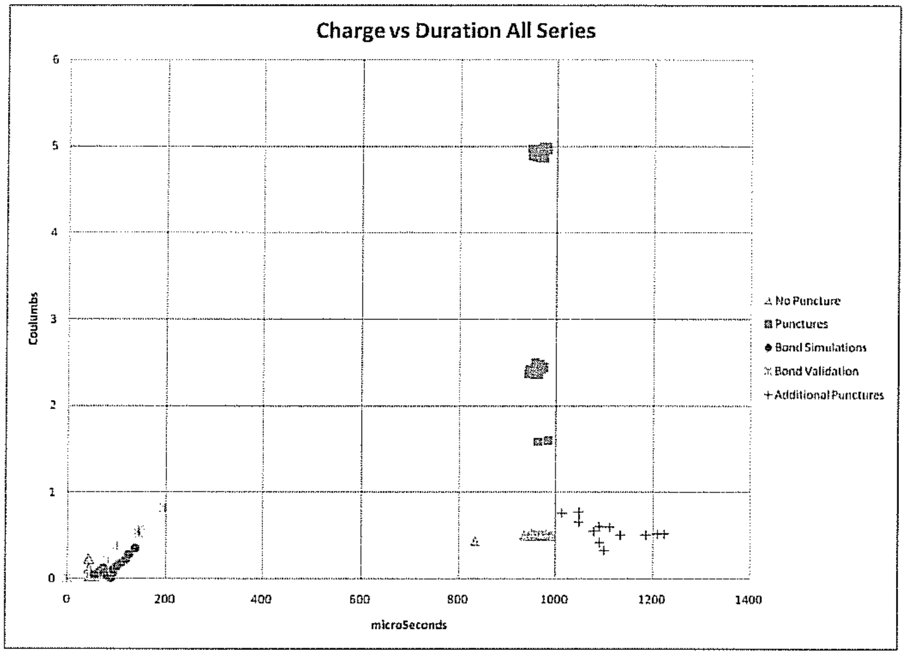

Figure 24 – Arc Charge versus Duration for All Data

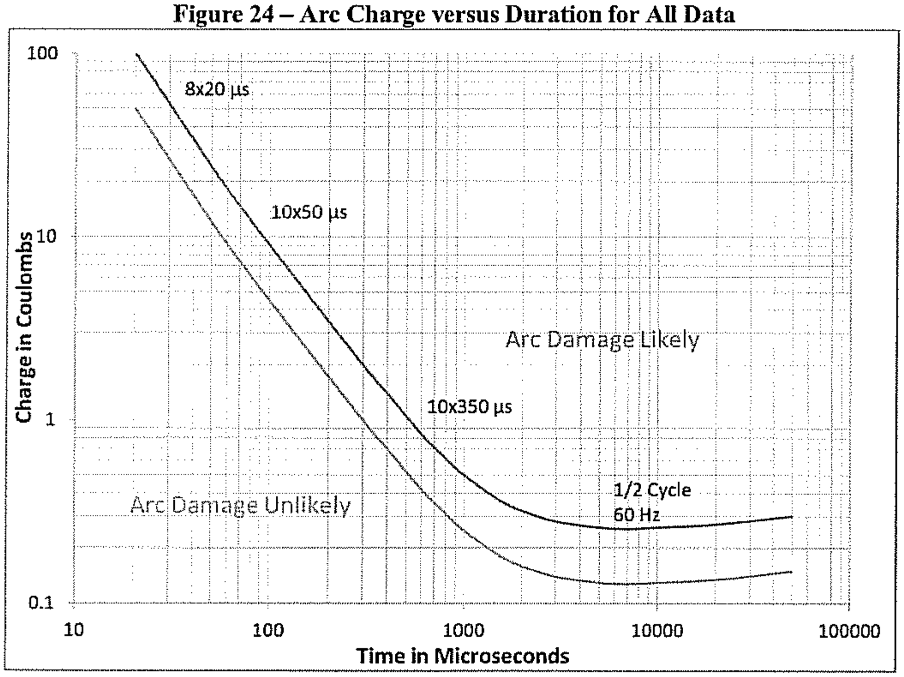

Figure 25 – Criterion Proposed by PowerCET

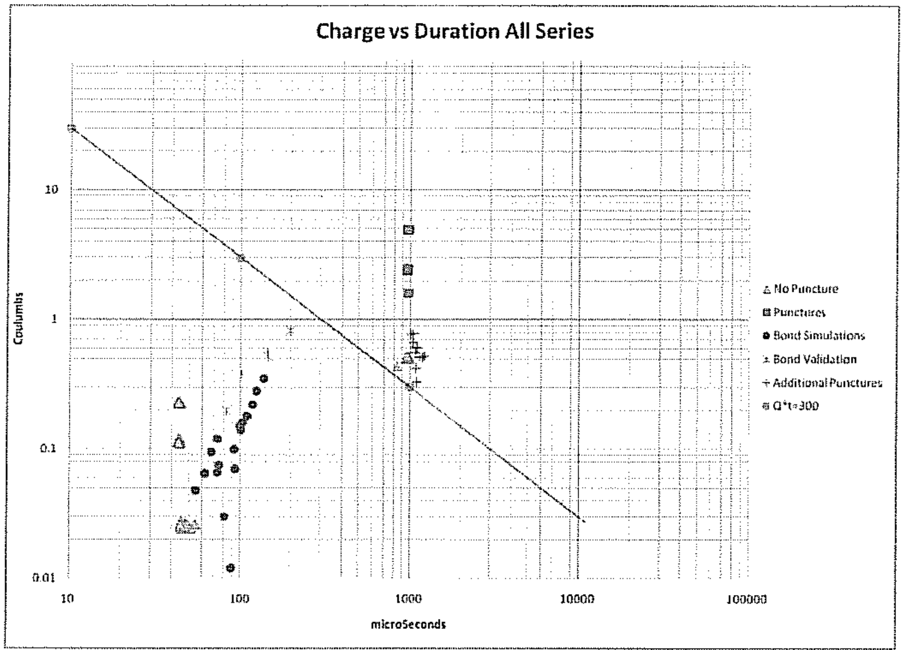

Figure 26 – Log Arc Charge versus Duration

Table 5 – Arc Time-Charge Products

Bond feet	I-peak	Q-arc	t -µS	Q*t
7	270	0.01	89	1
16	740	0.03	81	2
33	1500	0.07	93	7
49	2160	0.10	93	9
66	2770	0.14	101	14
82	3280	0.18	110	20
98	3720	0.22	118	26
131	4470	0.28	125	35
164	5060	0.35	138	48

Conclusions

The project work was planned and executed in order to address the following points:

1. Validate whether or not bonding of CSST is an adequate solution to lightning exposure problem.
2. If bonding is the solution, validate how bonding should be done.
3. If bonding is the solution, validate the size of the bonding jumpers.
4. Determine if bonding should be done at a location or locations other than where the gas pipe enters the building.
5. Determine if alternate methods can be used for safe installation, i.e., separation from other equipment.

The overall conclusion is that direct bonding of CSST to earth ground clearly limits the amount of charge available on the CSST during nearby lightning strikes versus the unbonded condition. Limiting the charge available was shown to prevent perforation of the CSST in all the simulated and observed cases that made use of a ground bond. Simulations of direct bonds of up to 164 feet (50 m) did not indicate perforation.

Perforation of the CSST was observed only in those instances where there was no direct bonding whatsoever. Even in the unbonded cases, a current on the order of 5 kA with a waveform of 10x350 μS was required to cause perforation. The amount of charge delivered in these cases is severe, representative of a lightning strike near the home.

Direct bonding of secondary gas manifolds did provide incremental benefit. Simulations indicate that the total available arc charge was reduced by an additional 20% when a manifold bond was used in conjunction with a primary bond.

The overall indication of the data is "shorter is better" with respect to bond length. A second round of simulations was performed that varied the bond conductor point of attachment from the gas service entrance to the middle of the CSST run and to the gas appliance. The motivation for this set of scenarios was to verify that all points of attachment were effective. When faced with the pragmatic decision of where to attachment the bonding conductor to the gas system, the data indicates that the shortest path to the structure earth ground is the most effective.

The data measured and simulations based on this data indicate that two conditions must be satisfied before a perforation can take place on the CSST: there must be sufficient charge present and the duration of an arc must be long enough. Without these two being satisfied, it is improbable that the metal can achieve a high enough temperature for perforation to occur. The critical value appears to be in the vicinity of $Q*t=300$ where t is in microseconds and Q is in Coulombs. Further work could refine this value.

Direct bonding substantially shortens the duration (t) of arcing, or eliminates it entirely, by providing alternative paths to dissipate the available charge, thus removing one of the necessary conditions for perforation. A simulated direct bond with a length of 164 feet provides a $Q*t$ of roughly 48.

The concept that there is a value of $Q*t$ above which damage can be expected is supported by the observed data that a long duration AC power fault current carried on CSST can lead to arc perforations. It would also indicate that a direct lightning strike may carry enough charge to cause damage; even though the duration is brief a large number of Coulombs (Q) may be transferred. This conclusion indicates that, while direct bonding will provide very broad protection from lightning damage, it does have limits.

The issue of CSST exhibiting unusual inductance properties due to its geometry or material properties was examined. The self-inductance of CSST was measured by two different methods, by suspending samples of CSST over a ground plane and by making coils of the CSST. In both methods the measured inductance values were very close to that predicted for a straight walled conductor of the same OD. The

coil method is preferred as it minimizes sources of experimental error. These inductance values were used in the simulation models to predict arc current and charge. The accuracy of these models were also verified as part of this testing. There is no real evidence to support the premise of unusual inductive properties.

These findings were developed through a combination of experimental work and simulations. Initial experimental work measured baseline parameters of CSST samples from several manufacturers and verified there was little variation from manufacturer to manufacturer. Using this data, simulations of a number of CSST and ground conductor configurations were carried out. A subset of the simulated configurations were set up in a laboratory and tested for verification. The agreement between the simulated and tested cases is described in the following excerpt from the PowerCET Final Report (Appendix E). Configurations involving extreme lengths of CSST and direct bond ground conductor could not be tested in the laboratory due to the real limitations of the current pulse generator.

All simulations produced predicted waveforms in the various paths that were close to those measured in the laboratory. Simulated peak current magnitudes differed by between 1% and 4% of those measured. Predicted waveforms were within about 5% of those measured, with the largest discrepancy being on the wave tail. These minor discrepancies occurred in cases where it was difficult to measure the inductance of the circuit in the presence of parallel conductors. In all cases, the simulated arc waves resulted in calculated charge transfer within 10% of that measured in the laboratory tests. These results are well within experimental error and quite sufficient to validate the simulation models for their intended purpose.

Given the finding that direct bonding of CSST can prevent perforation by dissipating energy; the concept of separating the CSST from other facilities must be re-examined. The typical residential HVAC systems bring gas, electricity, and sometimes water facilities together at a single node. While it would be possible (in new construction) to separate the facilities leading up to a furnace or boiler, maintaining the separation at the HVAC unit has practical problems. As engineering control to provide lightning protection, direct bonding is much more straightforward to implement.

If the bonding conductor length is constrained to 75 feet or less both perforation and arcing can be suppressed. Simulation supports this finding for three different attachment points of the bonding conductor to the gas system. As a practical consideration, the attachment point that gives the shortest conductor to the structure earth ground should be considered.

EXHIBIT "J"

List of Acronyms

Acronym	Description
LTI	Lightning Technologies Incorporated
CSST	Corrugated Stainless Steel Tubing
BIP	Black Iron Pipe
NFPA	National Fire Protection Agency
SPICE	Simulation Program with Integrated Circuit Emphasis

Appendices

A – NFPA Standards Council Decision #10-2

This decision document was produced by the NFPA Standards Council that deals with jurisdictional and technical aspects of CSST installation practice. In the technical realm calls for work to be performed that will lead to the technical substantiation of direct bonding practice for CSST that will address the following points.

- Validate whether or not bonding of CSST is an adequate solution to lightning exposure problem.
- If bonding is the solution, validate how bonding should be done.
- If bonding is the solution, validate the size of the bonding jumpers.
- Determine if bonding should be done at a location or locations other than where the gas pipe enters the building.
- Determine if alternate methods can be used for safe installation, i.e., separation from other equipment.

B - Validation of Installation Methods for CSST – Phase 2 v2 Proposal, November 2011

This proposal document "Validation of Installation Methods for CSST Gas Piping to Mitigate Lightning Related Damage – Phase 2 v2 (November 2011)" was produced by SEFTIM. This proposal was developed after the completion of the Phase 1 Study, a comprehensive review of the literature in this area along with case studies of damage incidents. The proposal describes a testing methodology that was substantially followed for this project. The proposal also identifies Lightning Technologies Incorporated and PowerCET as entities capable of performing portions of the test program.

C - CSST GAS PIPE LIGHTNING HIGH VOLTAGE AND HIGH CURRENT TESTS

This technical report "CSST Gas Pipe Lightning High Voltage and High Current Characterization Tests and Model Validation Tests" document was produced by Lightning Technology Incorporated. The subject matter of this report is the laboratory testing of the CSST product to characterize its physical properties and the follow-up testing of selected configurations of direct bonds to verify the accuracy of the simulation model. This testing collected information on the resistance, inductance, and capacitance per meter of the CSST product. The damage resistance of CSST to varying levels of arc current was quantified. Finally, selected configurations of CSST and direct bond ground conductor were subjected to arc currents and the results compared to simulations. The report gives a detailed account of the measurement methodology, instrumentation used, and a full catalog of the data collected.

D – Initial Simulations by PowerCET

This slide deck was produced by PowerCET for GTI. It contains a high level synopsis of the parametric measurements taken by LTI as a precursor to the simulations work by PowerCET. The presentation contains the results of a series of simulations produced by PowerCET after the basic parameter measurements were completed by LTI. PowerCET chose to use their own measured value of CSST resistance for these simulations, 40 mΩ/m for 1" diameter and 66 mΩ/m for 0.5", rather than those provided by LTI. The simulations indicate that a 6AWG copper direct bonding conductor applied at the point where the gas service enters the residence can prevent CSST perforations caused by lightning induced arcing. This model was used to propose scenarios for further testing at LTI for the purposes of validating the accuracy of the simulation model.

EXHIBIT "J"

E - VALIDATION OF INSTALLATION METHODS FOR CSST - REPORT

This report document "Validation of Installation Methods for CSST Gas Piping to Mitigate Lightning Related Damage" was produced by PowerCET. The version herein supersedes that provided with the May 2013 release the final report.

The PowerCET report covers several simulated cases of lightning energy introduced to the piping and electrical systems of a residential structure and how the distribution of energy amongst these systems is effected by ground bonding. The lightning energy was modeled using a 10x350 μS waveform at 10 kA.

The first set of scenarios make the assumption that the bonding conductor is always attached at the point where the gas service enters the structure. The scenarios model varying lengths of bonding conductor and the absence of any bonding conductor. The point of lightning energy injection was varied between the gas service entry and an electrical appliance. The CSST length was held constant at 100 feet and the bonding conductor (when present) varied from 24 feet (8m) to 164 feet (50m). Perforation was not indicated in any cases where the bonding conductor was in place; arcing was indicated for some of the greater lengths of bonding conductor.

An additional set of scenarios performed in September of 2013 is covered in this report. These scenarios replicate the first round in terms of energy injection and CSST length. The variation in this set of scenarios is that the point of ground bond attachment is varied to now include the gas appliance served by the CSST and the mid-point of the CSST run. The motivation for these additional scenarios was the 75 foot limit on the bonding conductor set by the NFPA 54 Research Committee. The ability to move the bonding point addresses the pragmatic concerns of how to install the shortest bonding conductor practical. Conductor lengths of 75 feet and 40 feet were simulated. In all simulations where the bonding conductor was present neither perforation or arcing was indicated.

The report also covers the follow up testing performed at LTI to validate the simulation model. A number of laboratory tests were set up to allow direct comparison of Scenario 1 simulations to measured results. The practical limitations of laboratory equipment did not allow for 30m lengths of CSST and bond wire to be tested; the current pulse generators cannot provide the requisite 10x350 waveform to that great of load impedance. The CSST length was standardized to 15 feet (4.5m) and the bonding conductor was tested in lengths from 1m to 16m. There was good agreement between the model predications and the experimental results. In all instances the total charge transferred through the arc, predicted and measured, agreed within 10%.

This report also contains a detailed treatment of the measurement of CSST inductance. The method of inductance measurement preferred by PowerCET is to form closed loop coils of CSST. This approach minimizes several sources of experimental error while making the measurement. The measurements of CSST inductance carried out in this manner provided results very close to those for a smooth walled tube of the same OD calculated using a standard (Rosa) formula. The results of the calculated and measured inductances for CSST also agreed within 10%.

END OF REPORT